Continental intra-arc depressions: A nonextensional model for their origin, with a Proterozoic example from Wopmay orogen

Robert S. Hildebrand
Precambrian Division, Geological Survey of Canada, Ottawa, Ontario K1A 0E4, Canada
Samuel A. Bowring
Department of Geology, University of Kansas, Lawrence, Kansas 66045

ABSTRACT

The 1.875–1.86 Ga Great Bear Magmatic Zone is a linear belt, 100 km wide by 800 km long, of low TiO_2, high Al_2O_3 volcanic rocks ranging continuously from basalt to rhyolite, cut by allied hornblende-biotite–bearing plutonic rocks. Comprehensive study of the facies, volcanic styles, chemistry, and petrography indicates that it is similar to Cenozoic continental arcs. Preservation of high-level volcanic rocks suggests that the zone never had an unusually thick crust and therefore is similar to some intra-arc depressions, such as the Mesozoic-Paleogene depression of Chile, common in younger continental arcs. These long, linear depressions are the sites for voluminous pyroclastic volcanism, contain sections tens of kilometres thick, and are zones of subsidence whose surface remains close to sea level. They originate when the mass of basaltic andesite arriving at the base of the crust equals the mass of vitric ash removed from the areas by high-level atmospheric transport during ash-flow eruptions.

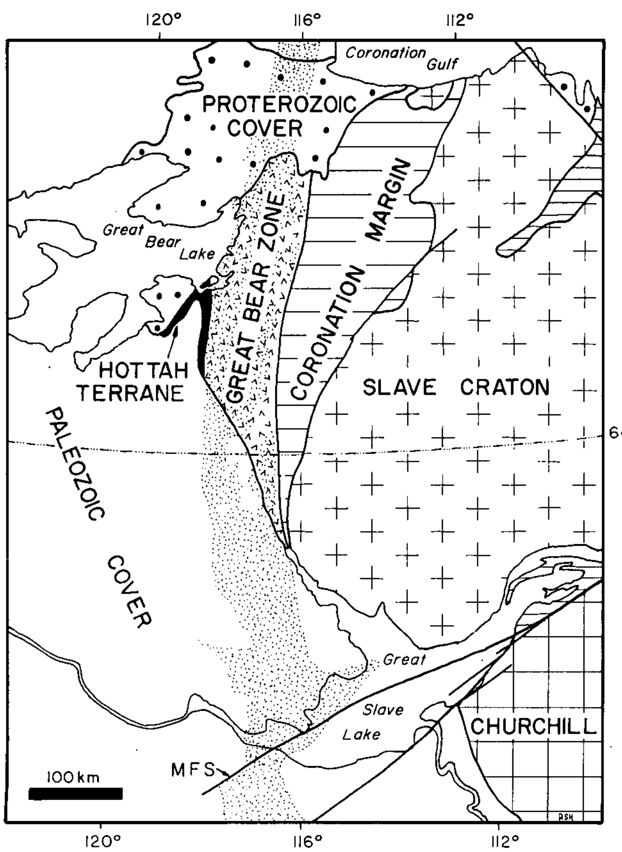

Figure 1. Location of major tectonic zones of Wopmay orogen. Dotted pattern shows extent of 200–300 γ aeromagnetic high associated with Great Bear Magmatic Zone. MFS = MacDonald-Wilson fault system, a post-arc dextral transcurrent fault.

INTRODUCTION

The term "Andean-type continental margin" is used to refer to a continental margin beneath which an oceanic plate is subducted to form a magmatic arc located upon the overriding continent. This has led to the general notion that continental arcs are zones of crustal thickening and uplift due to underplating by large volumes of mafic magma rising out of the mantle. Here we compare the Great Bear Magmatic Zone, an early Proterozoic continental volcanic arc located in the Wopmay orogen, to younger continental margin arcs, and we suggest that they are not necessarily zones of crustal thickening and uplift but, rather, low-lying regions containing broad areas of subsidence. We develop a model to explain the subsidence in terms of mass balance between mafic magma rising into the crust and siliceous ash removed from the areas by high-level atmospheric transport.

GREAT BEAR MAGMATIC ZONE

The Great Bear Magmatic Zone (1.875–1.86 Ga) occupies about 40,000 km^2 in the western part of the Wopmay orogen, an early Proterozoic north-trending, multicollisional orogen exposed in the northwestern Canadian Shield (Hoffman, 1980). The orogen is divisible into three major tectonic elements: the Coronation margin, the Great Bear Magmatic Zone, and the Hottah terrane (Fig. 1).

The Coronation margin comprises, in ascending order, initial rift volcanic and sedimentary rocks, siliciclastics and carbonates of a west-facing passive continental margin (Hoffman, 1980), and northwesterly derived foredeep deposits. These rocks were thrust eastward toward the Slave craton (Tirrul, 1983). In the western part of the margin, continental rise–prism rocks were strongly metamorphosed and intruded by numerous syntectonic peraluminous plutons (St-Onge et al., 1982).

The Hottah terrane, exposed only near the southeast corner of Great Bear Lake, is a belt of polydeformed metasedimentary and metavolcanic rocks, intruded by a diverse suite of deformed plutons ranging from diorite to granite. The terrane is considered to be a microcontinent, exotic with respect to the Coronation margin on the basis of geologic and geochronological evidence, beneath which attempted subduction of the leading edge of the Slave craton took place (Hildebrand et al., 1983).

Rocks of the Great Bear Magmatic Zone unconformably overlie both the Coronation margin and the Hottah terrane and bury the inferred suture between the two. In general, the zone comprises thick sequences of dominantly subaerial volcanic rocks, ranging continuously from basalt to rhyolite (Hildebrand, 1982) and mostly nonmarine sedimentary rocks cut by gregarious biotite-hornblende–bearing plutons, many of which are coeval with the volcanic rocks.

Voluminous intermediate to siliceous ash-flow tuffs and locally thick piles of andesite-basaltic andesite (high-Al basalt) dominate the supracrustal rocks. Many of the ash-flow tuffs can be related to specific cauldron complexes (Hildebrand, 1981, 1983). The Great Bear Magmatic Zone does not contain many synvolcanic faults, except ring-fracture systems, nor does it contain much in the way of coarse clastic detritus.

Magmatic rocks of the zone are chemically similar to Cenozoic suites classified as calc-alkaline (Fig. 2). In addition, calcic clinopyroxenes and amphiboles found in the andesitic rocks are similar to those occurring in younger high-K, calc-alkalic andesites. Rare-earth-element (REE) analyses of rocks from andesite to rhyolite exhibit light-REE enrichment patterns and the high overall abundances typical of high-K continental volcanic arcs (Hildebrand, 1982).

As exposed, the Great Bear Magmatic Zone is about 100 km wide by 400 km long, but it likely is at least 800 km long, as it forms a conspicuous linear aeromagnetic high (200–300 γ above that of surrounding rocks) of almost constant width that shows through thin Paleozoic and Proterozoic sedimentary cover at both its northern and southern limits of exposure (Fig. 1). The facies, eruptive styles, mineralogy, chemistry, and great linearity of the Great Bear Magmatic Zone indicate that it is part of an early Proterozoic continental volcanic arc.

Synclinal Basins of Continental Magmatic Arcs

The preservation of stratovolcanoes and other high-level volcanic rocks in the Great Bear Magmatic Zone suggests that the region never had an unusually thick crust and was probably subsiding during volcanism, because if the crust was abnormally thick, then the volcanic rocks would have been quickly eroded due to isostatic uplift. While continental volcanic arcs often have parts, or individual stratovolcanoes, that are topographically high-standing, most do not have the thick crust of the Peruvian Andes but have normal 30–35-km-thick crust and commonly contain large areas of subsidence. Recent work by Knight and Murphy (1980) and Feininger (1983) and maps by Cobbing (1981) imply that the cause of the unusually thick crust in the Peruvian Andes is not due to underplating but more probably to a pre-arc collision of a west-facing passive margin sequence with one or more exotic terranes.

The structure and volcanism of the Great Bear Magmatic Zone display remarkable similarities to a type of depression found in some continental volcanic arcs: the Mesozoic-Paleogene volcanic belt of Chile (Zeil, 1979; Levi and Aguirre, 1981), the coastal lowlands of Hokkaido, Japan (Oide, 1968), and possibly the "graben-synclines" of Kamchatka (Erlich, 1968). The depressions, which lay at elevations close to sea level for many millions of years, indicating that they remained in isostatic equilibrium, are about 100 km across and several hundred kilometres long and are loci for voluminous pyroclastic eruptions and cauldrons.

The depressions are not continental rifts in the classic sense. Although faulting is common, there is little evidence, if any, for the listric normal faulting and concomitant rotation of crustal blocks that seem to characterize continental rifts such as the western Basin and Range province and the Afar region. Instead, the regional structure of the depressions is generally that of huge synclines of volcanic and sedimentary rocks tens of kilometres in apparent thickness. In the Mesozoic-Paleogene depression of Chile, for example (Fig. 3), the sections comprise a series of overlapping lenses whose aggregate thickness exceeds that of the crust (Levi and Aguirre, 1981). Within the Great Bear Magmatic Zone stratigraphic thicknesses are in excess of 35 km.

Origin of Continental Arc Magmatism

There can be little doubt that batholiths and associated siliceous volcanic rocks of continental margin arcs are generated dominantly in the crust, for in volcanic arcs built on oceanic crust there are no batholiths comparable to those of western North and South America, only small intrusions of tonalite, trondhjemite, and plagiogranite (Waters, 1948; Bateman, 1981). In this regard, the Kurile-Kamchatka and Aleutian-Alaska Peninsula arcs are particularly instructive because both pass longitudinally from oceanic to continental crust. On continental crust, volcanic products are much richer in silica and incompatible elements, much greater amounts of pyroclastic material are erupted in the form of ash-flows, and large composite batholiths are emplaced into the volcanic suprastructure. These are fundamental differences that clearly indicate that continental crust is involved in the generation of batholiths and their related eruptive products. A similar conclusion is reached from study of isotopic data from

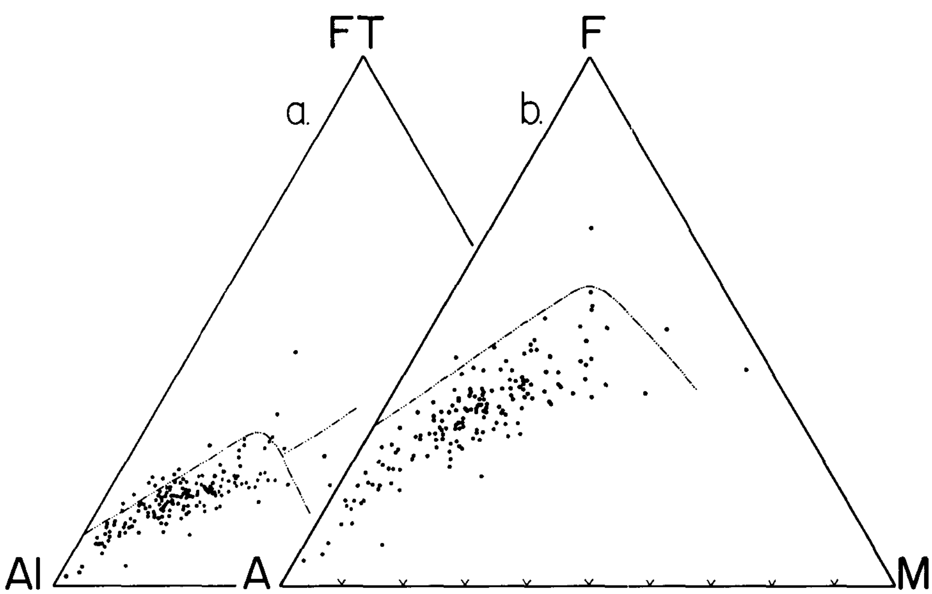

Figure 2. a: Jensen (1976) cation plot of rocks from Great Bear Zone; Al = Al_2O_3, FT = FeO + Fe_2O_3 + TiO_2; b: AFM diagram for same rocks; tholeiitic–calc-alkaline dividing line from Irvine and Baragar (1971).

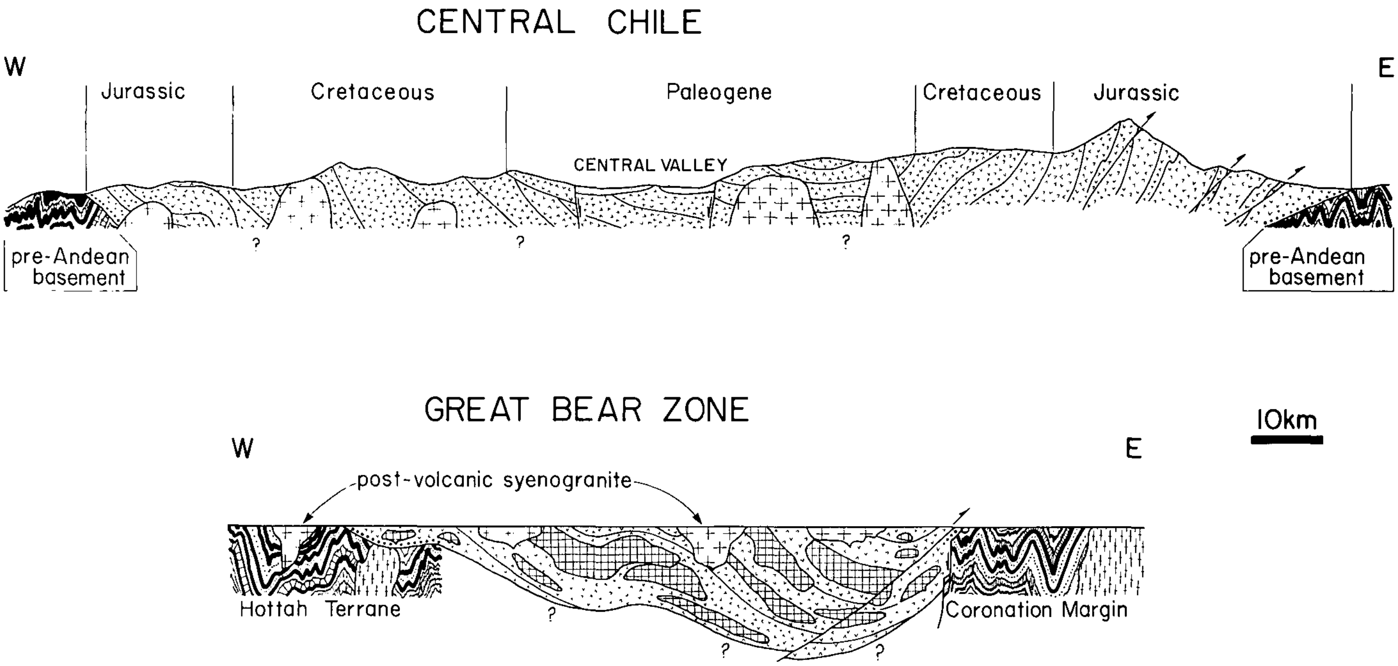

Figure 3. Schematic cross sections comparing Mesozoic-Paleogene depression of Chile (from Levi and Aguirre, 1981) with Great Bear Magmatic Zone (from Hoffman, unpub.).

continental arcs (Zartman, 1974; Carter et al., 1978; Tilton and Barreiro, 1980; DePaolo, 1981; James, 1981) as well as experimental phase petrology (Wyllie et al., 1976; Wyllie, 1977) and petrological considerations (Presnall and Bateman, 1973).

Yet, ever since it was recognized that parts of the continental crust are enriched in radiogenic ^{87}Sr relative to the upper mantle (Faure and Hurley, 1963), it has been argued that batholiths of continental arcs with low initial $^{87}Sr/^{86}Sr$ were mantle derived. However, low initial Sr ratios do not by themselves indicate a direct mantle origin. For example, there are several mechanisms for deriving magmas with low initial $^{87}Sr/^{86}Sr$ other than direct melting of the mantle. These include (1) melting of juvenile continental crust ultimately derived from the mantle; (2) melting of lower crustal rocks with low Rb/Sr, such as depleted granulites (Heier, 1973); (3) melting lower continental crust that has isotopically re-equilibrated, perhaps with the aid of a fluid phase, with the large mantle reservoir (Armstrong, 1968; Collerson and Fryer, 1978); and (4) mixing of crustally derived magmas with magmas derived from mantle material.

In light of the above, we find it difficult to accept the view, based mainly on strontium-isotope data, that batholiths of continental arcs and their consanguineous volcanic rocks are generated directly in the mantle (Brown and Hennessey, 1978; Atherton et al., 1979; Thorpe et al., 1979; Cobbing and Dennis, 1982). An example of mechanism 4 is found in the Holocene Edgecumbe volcanic field of southeast Alaska, where hybrid melts, generated by the influx of mantle-derived basalt into sialic crust, partial melting of that crust, and subsequent mixing to produce rhyodacite, andesite, and dacite, all have initial $^{87}Sr/^{86}Sr$ less than 0.7048 (Myers and Marsh, 1981).

The Sm-Nd isotopic system used in conjunction with Rb-Sr isotopes apparently rules out the possibility that batholiths of continental arcs are derived from old continental crust with low Rb/Sr ratios (see DePaolo, 1981) but does not rule out possibilities 1, 3, and 4 above. Even the Lu-Hf isotopic system apparently cannot rule out possibilities 1 and 4 if the juvenile crust is less than 150 m.y. old (Patchett et al., 1981).

If much of the magmatism of continental volcanic arcs is generated by crustal anatexis, as suggested here, then the mechanism of melting must be consistent with an unthickened crust, subsidence, and epizonal plutonism—all of which we suggest are characteristic of continental volcano-plutonic arcs. The crust can be melted by crustal thickening due to thrusting, folding, or underplating, by addition of water, or by the influx of hot, mafic magma. Addition of mafic magma appears to be the only mechanism capable of creating the observed magmatism, because crustal thickening will lead to uplift while addition of water will create melts that are unable to rise to high crustal levels. Therefore, we adopt the view that mafic magma, similar in origin and composition to island-arc basaltic andesite (high-alumina basalt), rises into the lower crust and causes widespread partial melting. Calculations by Marsh (1983) suggest that under most conditions basalt emplaced into the lower crust, especially in the form of multiple intrusions, may contain enough energy to generate an equivalent or greater volume of siliceous magma (see also Patchett, 1980).

Origin of the Synclinal Basins

If, as we suggested earlier, the synclinal basins do indeed form a distinct class of basins formed in continental arcs, and they do not originate by extension, to what do they owe their origin? We suggest that the mechanism may be crustal sagging, or downwarping, due mostly to loss of material out of the immediate vicinity of the basins by airfall associated with the voluminous ash-flow tuff eruptions (Fig. 4).

Consider that during ash-flow eruptions as much as half the erupted volume occurs as fine vitric ash that rises to great heights in the atmosphere as a turbulent cloud and ultimately is widely dispersed by high-level wind (Fisher, 1966; Walker, 1981; Flood et al., 1980; Izett, 1981). Consider also that the average center may erupt between 300 and 600 km^3 of material and each synclinal basin contains many such centers. Therefore, the volume of ash-flow tuff present in the synclines is on the order of tens of thousands, perhaps even hundreds of thousands of cubic kilometres.

Because the synclinal basins under consideration here are topographically low-standing features located close to sea level, and have remained so for many millions of years after volcanism ceases, the crust in the areas probably was not thickened by underplating and remained in isostatic equilibrium. If the relative mass of material added to the crust from below is less than that lost from the areas by atmospheric transport, there would be a net loss of crustal material from the area of the surface volcanism, leading to subsidence. If the mass of material added to the crust is larger than that lost, the crust would be thickened and tend to rise isostatically because basalt is less dense than mantle peridotite. Thus, in order for the regions to remain at more or less the same elevations with respect to sea level, the mass of basaltic andesite added to the crust must equal the mass of vitric ash erupted and removed from the immediate area. Approximate values for the density of basaltic andesite are about 2.5 g/cm^3 in the temperature range of 1200–1400 °C, whereas those for rhyolitic melts at 800 °C are about 2.3 g/cm^3 (Murase and McBirney, 1973). The density difference between the two is about 8% and therefore the two volumes must be about equal. The lower crust will, in all likelihood, become denser as the basaltic andesite crystallizes to mafic

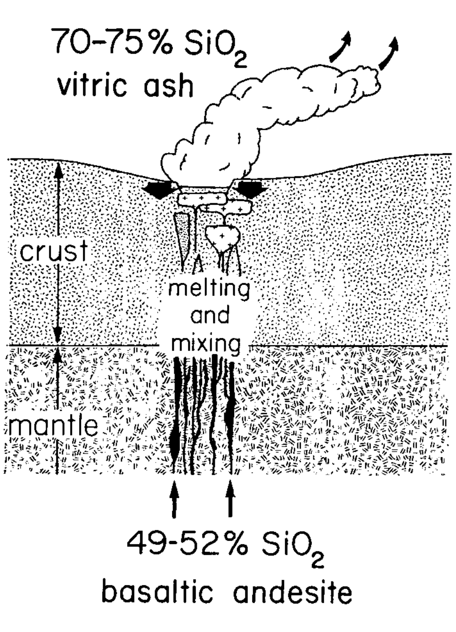

Figure 4. Illustration of model for origin of intra-arc synclinal basins.

granulite—a rock denser than partial melts generated by the influx of basaltic andesite. However, the middle and upper crust may become less dense as a result of the migration and crystallization of less dense magmas generated in the deep crust. Without knowing the composition of the crustal column it is impossible to evaluate these effects quantitatively. Nevertheless, the mass of material added to the crust must still approximate the mass of material lost if the region is to remain in isostatic equilibrium. We consider that the amount of magma arriving at the base of the crust in continental arcs is similar to the volume of magma erupted and intruded in modern island arcs. Estimates for this volume range between 1 and 10 km^3/m.y./km of arc (Marsh, 1979).

Our model is consistent with the pyroclastic eruption rates in well-mapped parts of volcanic arcs such as the San Juan volcanic field, southwestern Colorado, a 100-km-long segment of an arc of Tertiary age extending southward to the Sierra Madre Occidental (Lipman, 1980). Steven and Lipman (1976) estimated that in the San Juan volcanic field about 9,000 km^3 of pyroclastic ejecta were erupted between 30 and 22 m.y. ago. That is equivalent to a rate of about 1,100 km^3 $m.y.^{-1}$ or 11 km^3/km. Therefore, as much as 5.5 km^3 of vitric ash may have been erupted out of the region for every 1 km/m.y. This approximation is well within the estimated range of eruption and intrusion in island arcs developed on oceanic crust.

Francis and Rundle (1976) estimated the volume of ash-flow tuff present in a 115-km-long section of the central Andes to be 1.5×10^3 km^3 and arrived at a rate of production equal to 1.3 km^3 $m.y.^{-1}$ km^{-1}. Although they were aware that ash flows may lose 50% of their volume by high-level atmospheric transport, their calculations were based only on the volume of tuff preserved. Thus, the rate at which vitric ash was erupted and removed from the area may have been about 1.3 km^3 $m.y.^{-1}$ km^{-1}—again a volume similar to that inferred to be arriving at the base of the crust.

CONCLUSIONS

Our estimates for the volume of vitric ash lost from the depressions are of the same magnitude as estimates for the volume of basaltic andesite (high-Al basalt) believed, by analogy with magmatic rates in oceanic arcs, to be arriving at the base of the continental crust. Thus, the depressions are able to remain in isostatic equilibrium. The areas subside because material is constantly being removed from the lower crust and erupted onto the surface.

The calculations can also be used to place constraints on the origin of magmatism in continental volcanic arcs. For example, since the volume of mafic magma inferred to arrive at the base of the crust is about equal to the volume of vitric ash lost, then the total volume of magma erupted and intruded in continental arcs must be even greater. Therefore, it is not possible for continental arc margmas other than basaltic andesite or perhaps andesite to be derived from mafic magmas by any type of differentiation, for about 10 volumes of mafic magma are needed to generate 2 volumes of magma with the composition of granodiorite. This argument and their consistent absence where there is no continental crust virtually demand that batholiths and their volcanic counterparts be the products of continental crust.

REFERENCES CITED

Armstrong, R. L., 1968, A model for the evolution of strontium and lead isotopes in a dynamic earth: Reviews of Geophysics, v. 6, p. 175–199.

Atherton, M. P., McCourt, W. J., Sanderson, L. M., and Taylor, W. P., 1979, The geochemical character of the segmented Peruvian Coastal batholiths and associated volcanics, *in* Atherton, M. P., and Tarney, J., eds., The origin of granite batholiths: Geochemical evidence: Orpington, England, Shiva Publishing Ltd., p. 45–64.

Bateman, P. C., 1981, Geologic and geophysical constraints on models for the origin of the Sierra Nevada batholith, California, *in* Ernst, W. G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 71–86.

Brown, G. C., and Hennessey, J., 1978, The initiation and thermal diversity of granite magmatism: Royal Society of London Philosophical Transactions, v. 288, p. 631–643.

Carter, S. R., Evensen, N. M., Hamilton, P. J., and O'Nions, R. K., 1978, Neodymium and strontium isotope evidence for crustal contamination of continental volcanics: Science, v. 202, p. 743–747.

Cobbing, E. J., 1981, Geological map of the Western Cordillera of northern Peru, *in* Cobbing, E. J., Pitcher, W. S., Wilson, J. J., Baldock, J. W., Taylor, W. R., McCourt, W. J., and Snelling, N. J., The geology of the Western Cordillera of northern Peru: Institute of Geological Sciences Overseas Memoir 5, 143 p., scale 1:500,000.

Cobbing, E. J., and Dennis, J. G., 1982, Discussion on the origin of granites: Geological Society of London Journal, v. 139, p. 103–105.

Collerson, K. D., and Fryer, B. J., 1978, The role of fluids in the formation and subsequent development of early continental crust: Contributions to Mineralogy and Petrology, v. 67, p. 151–167.

DePaolo, D. J., 1981, A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granite batholiths of the Sierra Nevada and Peninsular Ranges, California: Journal of Geophysical Research, v. 86, p. 10470–10488.

Erlich, E. N., 1968, Recent movements and Quaternary volcanic activity within the Kamchatka Territory: Pacific Geology, v. 1, p. 23–39.

Faure, G., and Hurley, P. M., 1963, The isotopic composition of strontium in oceanic and continental basalt: Application to the origin of igneous rocks: Journal of Petrology, v. 4, p. 31–50.
Feininger, T., 1983, Allochthonous terranes in the Andes of Ecuador and northwestern Peru: Geological Association of Canada Abstracts with Programs, v. 8, p. A22.
Fisher, R. V., 1966, Mechanism of deposition from pyroclastic flows: American Journal of Science, v. 264, p. 350–363.
Flood, R. H., Shaw, S. E., and Chappell, B. W., 1980, Mineralogical and chemical matching of plutonic and associated volcanic units, New England Batholith, Australia: Chemical Geology, v. 29, p. 163–170.
Francis, P. W., and Rundle, C. C., 1976, Rates of production of the main magma types in the central Andes: Geological Society of America Bulletin, v. 87, p. 474–480.
Heier, K. S., 1973, Geochemistry of granulite facies rocks and problems of their origin: Royal Society of London Philosophical Transactions, v. A273, p. 429–442.
Hildebrand, R. S., 1981, Early Proterozoic LaBine Group of Wopmay Orogen: Remnant of a continental volcanic arc developed during oblique convergence, *in* Campbell, F.H.A., ed., Proterozoic basins of Canada: Geological Survey of Canada Paper 81-10, p. 133–156.
—— 1982, An early Proterozoic continental volcanic arc at Great Bear Lake, Northwest Territories [Ph.D. thesis]: St. John's, Memorial University of Newfoundland, 237 p.
—— 1983, Geology of the Rainy Lake and White Eagle Falls map areas, District of Mackenzie: Early Proterozoic cauldrons, stratovolcanoes and subvolcanic plutons: Geological Survey of Canada Paper 83-20.
Hildebrand, R. S., Bowring, S. A., Steer, M. E., and Van Schmus, W. R., 1983, Geology and U-Pb geochronology of parts of the Leith Peninsula and Rivière Grandin map areas, District of Mackenzie, *in* Current research, Part A: Geological Survey of Canada Paper 83-1A, p. 329–342.
Hoffman, P. F., 1980, Wopmay Orogen: A Wilson Cycle of early Proterozoic age in the northwest of the Canadian Shield, *in* Strangway, D. W., ed., The continental crust and its mineral resources: Geological Association of Canada Special Paper 20, p. 523–549.
Irvine, T. N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, p. 523–548.
Izett, G. A., 1981, Volcanic ash beds: Recorders of upper Cenozoic silicic pyroclastic volcanism in the western United States: Journal of Geophysical Research, v. 86, p. 10200–10222.
James, D. E., 1981, The combined use of oxygen and radiogenic isotopes as indicators of crustal contamination: Annual Reviews of Earth and Planetary Sciences, v. 9, p. 311–344.
Jensen, L. S., 1976, A new cation plot for classifying subalkaline volcanic rocks: Ontario Division of Mines Miscellaneous Paper 66, 22 p.
Knight, R., and Murphy, W., 1980, The effect of allochthonous bodies on subduction processes in the central Andes: EOS (American Geophysical Union Transactions), v. 61, p. 1114.
Levi, B., and Aguirre, L., 1981, Ensialic spreading-subsidence in the Mesozoic and Paleogene of central Chile: Geological Society of London Journal, v. 138, p. 76–81.
Lipman, P. W., 1980, Cenozoic volcanism in the western United States: Implications for continental tectonics, *in* Continental tectonics: Washington, D.C., National Academy of Sciences, p. 161–174.
Marsh, B. D., 1979, Island-arc volcanism: American Scientist, v. 67, p. 161–172.
—— 1983, Mechanics and energetics of magma formation and ascension, *in* Boyd, J., ed., Explosive volcanism: Washington, D.C., National Academy of Sciences.
Murase, T., and McBirney, A. R., 1973, Properties of some common igneous rocks and their melts at high temperatures: Geological Society of America Bulletin, v. 84, p. 3563–3592.
Myers, J. D., and Marsh, B. D., 1981, Geology and petrogenesis of the Edgecumbe volcanic field, S.E. Alaska: The interaction of basalt and sialic crust: Contributions to Mineralogy and Petrology, v. 77, p. 272–287.
Oide, K., 1968, Geotectonic conditions for the formation of the Krakatau-type calderas in Japan: Pacific Geology, v. 1, p. 119–135.
Patchett, P. J., 1980, Thermal effects of basalt on continental crust and crustal contamination of magmas: Nature, v. 283, p. 559–561.
Patchett, P. J., Kouva, O., Hedge, C. E., and Tatsumoto, M., 1981, Evolution of continental crust and mantle heterogeneity—Evidence from Hf isotopes: Contributions to Mineralogy and Petrology, v. 78, p. 279–297.
Presnall, D. C., and Bateman, P. C., 1973, Fusion relations in the system $NaAlSi_3O_8$-$Ca_2Al_2SiO_8$-$KAlSi_3O_8$-SiO_2-H_2O and generation of granitic magmas in the Sierra Nevada batholith: Geological Society of America Bulletin, v. 84, p. 3181–3202.
St-Onge, M. R., King, J. E., and Lalonde, A. E., 1982, Geology of the central Wopmay Orogen, Bear Province, District of Mackenzie: Redrock Lake and the eastern portion of the Calder River map areas, *in* Current research, Part A: Geological Survey of Canada Paper 82-1A, p. 99–108.
Steven, T. A., and Lipman, P. W., 1976, Calderas of the San Juan volcanic field, southwestern Colorado: U.S. Geological Survey Professional Paper 958, 35 p.
Thorpe, R. S., Francis, P. W., and Moorbath, S., 1979, Rare earth and strontium evidence concerning the petrogenesis of North Chilean ignimbrites: Earth and Planetary Science Letters, v. 42, p. 359–367.
Tilton, G. R., and Barreiro, B. A., 1980, Origin of lead in Andean calc-alkaline lavas, southern Peru: Science, v. 210, p. 1245–1247.
Tirrul, R., 1983, Structure cross-sections of Asiak Thrust-Fold Belt, Wopmay Orogen, District of Mackenzie, *in* Current research, Part B: Geological Survey of Canada Paper 83-1B, p. 253–260.
Walker, G.P.L., 1981, Generation and dispersal of fine ash and dust by volcanic eruptions: Journal of Volcanology and Geothermal Research, v. 11, p. 81–92.
Waters, A. C., 1948, Discussion, *in* Gilluly, J., ed., Origin of granite: Geological Society of America Memoir 28, p. 104–108.
Wyllie, P. J., 1977, Crustal anatexis: An experimental review: Tectonophysics, v. 43, p. 41–71.
Wyllie, P. J., Huang, W., Stern, C. R., and Maaloe, S., 1976, Granitic magmas: Possible and impossible sources, water contents, and crystallization sequences: Canadian Journal of Earth Sciences, v. 13, p. 1007–1019.
Zartman, R. A., 1974, Lead isotope provinces in the Cordillera of the western United States and their geologic significance: Economic Geology, v. 69, p. 792–805.
Zeil, W., 1979, The Andes: A geological review: Berlin, Gebruder Borntraeger, 260 p.

ACKNOWLEDGMENTS

We thank P. F. Hoffman, R. Tirrul, B. Marsh, and M. B. Lambert for their critical reviews of the manuscript.

Manuscript received May 2, 1983
Revised manuscript received September 23, 1983
Manuscript accepted October 5, 1983

Reviewer's comment

I really don't agree with everything in this paper, but it pulls together several fundamental concepts of arc volcanism and crustal evolution held by specialists in several, but hardly overlapping, areas.

Bruce Marsh